MODELING AND MEASUREMENT OF FIELD AND FLUX OF MPI

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SUMMARY

Magnetic particle inspection (MPI) is one of the oldest NDT techniques and it is the most common method used to detect surface defects in ferromagnetic materials. But since the beginning MPI has been based on experiments, experience and on subjective judgements. This contribution shows for the first time how MPI of complex shaped parts can be designed objectively by applying Maxwell equations and finite element calculations. The comparison between modelling and measurement shows substantial agreement. Results are given and discussed especially for automotive components like crankshaft and hub under DC- as well as AC-magnetization using coils and yokes.

INTRODUCTION

Magnetic particle inspection has been used for about 70 years /1/. Without doubt it is for ferromagnetic materials the most sensitive NDT technique ref. to surface defect detection and the least sensitive technique as far as disturbing boundary conditions are concerned: defects with dimensions above 1x10x100 μm^3 (width x depth x length) are found and geometry, surface roughness, microstructure, stresses and even crack closure /2/ do not decrease the defect detection capability.

Besides the economically irrelevant use of permanent magnets the method is based on current (i) induced magnetic fields (H) which produce a flux density (B) inside the material and a leakage flux or stray field (H_S) in the air above surface opening cracks. The stray field attracts magnetic particles, mostly suspended in liquids and surrounded with fluorescent dye. Therefore under UV-light crack indications are obtained with high contrast. Magnetizations of components are realized using yokes, coils and currents.

A few laws are known and applied:

$H(r) = i/(2\pi r)$

for the field at distance r from a current carrying wire,

$H = ni/l$

for the field in a coil of length l and of n turns,

$B = \mu(H) \cdot H$

for the flux density inside the material with $\mu(H) = \mu_o \mu_r(H)$, while $\mu_o = 4\pi \cdot 10^{-7}$ Vs/(Am) is the vacuum permeability and $\mu_r(H)$ is the material and field dependent relative permeability which makes the B-H-characteristic nonlinear.

Applications in practice have shown that tangential field strengths $\lesssim 60$ A/cm, tangential flux densities $\lesssim 1$ Tesla and normal stray field components $\lesssim 10$ A/cm are values guaranteeing the detection of cracks oriented perpendicular to the incident field.

But the design of a magnetic particle inspection system is extremely difficult for complex components as shown for example in Figures 1,2. For an automotive part the detection of defects has to be assured for any orientation and everywhere at the surface. Here multicircuit-magnetization is applied based on experience, experiments and subjective judgement. It is a totally unsatisfactory situation to design 5, 7 or 9 magnetization circuits using yoke, coil and/or current just by trial and error.

On the other hand it is well known that eddy current testing /3/, potential drop testing /4/ or electromagnetic machines in general /5/ can be modelled using numerical methods. The problem was how to transfer this knowledge to the special situation of magnetic particle inspection.

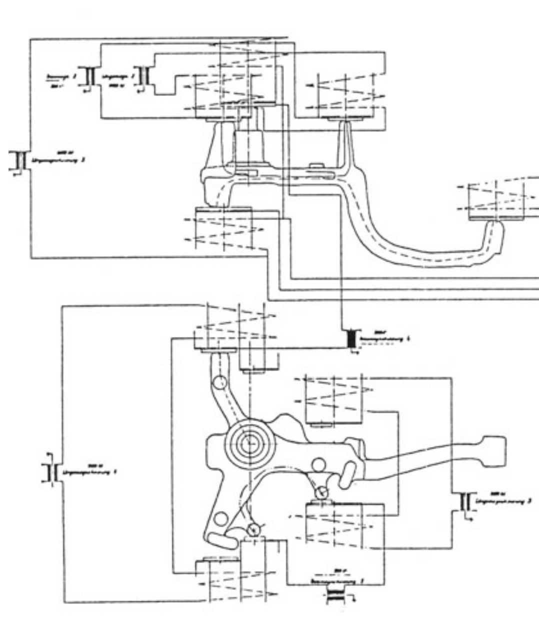

Fig. 1. Steering knuckle

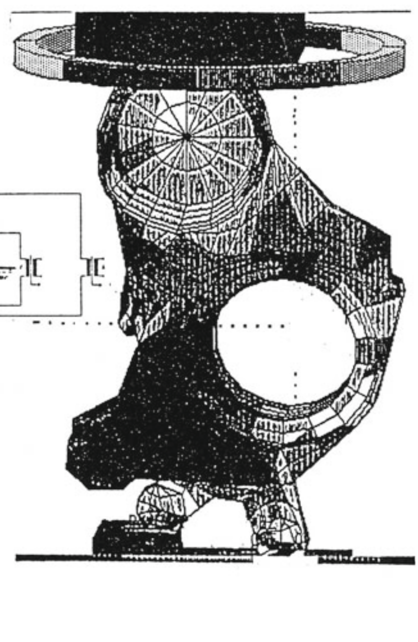

Fig. 2. Hub

Three aspects of magnetic particle inspection procedures need to be analyzed. The magnetic particles become magnetised in a small field and experience a force that depends on the gradient of this field. The spatial extent and magnitude of the field produced by a material defect is therefore important and there is clearly a relationship between the minimum size defect that can be detected, the size of particle used and its mobility. Analytic solutions that predict the fields produced by surface breaking defects /6/ and calculation of particle trajectories /7/ provide an essential background for the development of MPI methods. Unfortunately analytic solutions can only be found for simple geometries. Numerical methods must be used to model complex components in order to predict the surface fields, especially when the material has a non-linear magnetic characteristic, and to analyze the fields and forces that will be produced by irregular defects. Numerical methods can be used to complement the results from experimental measurements, for example, variations in material properties can be studied on the computer with a degree of control that cannot be achieved in an experiment.

A low frequency subset of Maxwell's equations describe all aspects of electromagnetic fields that are relevant to magnetic particle inspection modeling. The differential forms of these equations can be solved using a discrete approximation such as finite differences or finite elements, but the finite element approach is able to model components with more complicated surface shapes and small size features. In section 2 a short introduction to finite element methods for electromagnetic fields is shown and problems specific to MPI procedures are discussed.

MODELING MAGNETIC PARTICLE INSPECTION

Electromagnetic Fields equations

Power frequency or static fields and currents used for magnetic particle inspection can be described by a subset of Maxwell's equations neglecting the displacement current terms

$$\nabla \cdot B = 0 \tag{1}$$
$$\nabla \times H = J \tag{2}$$
$$\nabla \times E = -\dot{B} \tag{3}$$
$$\nabla \cdot J = 0 \tag{4}$$

where B is the magnetic flux density, H the magnetic field intensity, J the electric current density and E the electric field intensity. The material constitutive relationships relate these fundamental field quantities

$$J = \sigma E \tag{5}$$
$$B = \mu H \tag{6}$$

where μ is the materials permeability and σ its conductivity. Equation (1) implies that B can be defined as

$$B = \nabla \times A \tag{7}$$

where A is the magnetic vector potential.

Combining equations (2) and (3), using the magnetic vector potential defined by equation (7) gives the partial differential equation which is often used as the basis for a numerical solution

$$\nabla \times \frac{1}{\mu} \nabla \times A = - \sigma \dot{A} \tag{8}$$

Where the field and geometry are rotationally symmetric or can be assumed to be invariant in one dimension, equation (8) uniquely defines the vector potential providing that a constant of integration is determined from the topology of the current flow circuit /8/. In a fully three dimensional system the vector potential is only uniquely defined if σ is non-zero. In other cases a gauge condition must be imposed /9/.

In three dimensions in a non-conducting space or when the fields are static and the current is zero in the space, equation (8) and the vector potential unknown are unnecessarily complicated and expensive to solve. The magnetic field intensity H in such a space can be represented as

$$H = - \nabla \psi \tag{9}$$

because $\nabla \times H = 0$. This scalar potential approach can be combined with the concept of splitting the field intensity according to the source of the field /10/. Here the total field H is represented as the sum of at least two components

$$H = H_s + H_m \tag{10}$$

H_s may be the field produced by a local current, whereas H_m is rotation free and may be represented as the gradient of a scalar potential. This approach leads to a very efficient algorithm for static magnetic fields in three dimensions, and it can be combined with equation (8) in order to solve eddy current applications /11/.

Finite element discretization

Two basic methods can be used to solve continuum field problems. If the equations defining the field are written in partial differential form a local approximation to the field must be defined throughout space. It is convenient to achieve this by discretising space into simple sub-domains and using a local approximation function in each sub-domain. Alternatively, the equations could be expressed in an integral form where only the source distribution has to be approximated. The integral approach is limited to geometries that are not too complicated. The term finite element method is usually applied to a procedure based on the partial differential equation representation. The discretization in such a method is based on simplexes or hexahedra and the local approximation is a low order polynominal that is characterized by function values at a number of points in each sub-domain.

The equations defining the field may be solved using a weighted residual method or by using the underlying variational principal that can often be identified. In both cases it is usual to weaken the continuity conditions that would be imposed on the discrete approximation. This is achieved by performing a partial integration of the weighted residual form, hence reducing the continuity required from the field approximation functions /12/.

Magnetic Particle Inspection

The finite element method has been used to solve the partial differential equation for the vector potential (equation (8)) in order to calculate both static, AC and transient magnetic fields. In three dimensions the scalar potential method has been introduced to solve static problems and in the non-conducting space to reduce the cost of the analysis. In order to determine the excitation required for inspection of a complex component a full three dimensional model has been created. Figure 3 shows a finite element model of one quarter of a crankshaft and it includes vectors showing the field direction and magnitude on the component surface, calculated with an AC-50 Hz excitation. The fields have been calculated for DC and AC excitation, the model required 10,000 finite elements and 10,000 unknowns for the DC non-linear material solution. The AC excitation was solved using a time harmonic (frequency domain) substitution. In order to use this substitution the permeability and conductivity may vary with position but must be constant in time, this model had the same number of elements but 14,500 unknowns.
The modeling of complex components is only restricted by the difficulty of preparing a finite element discretization, not only of the component but also of the surrounding space which may include excitation yokes. Detailed modeling of a defect in addition to the full component model is impractical, the cost of analysing a wide range of defect shapes, material property variations and field levels would be too great. Defects have therefore been modeled independently using both 2 and 3 dimensional simulations /13/. In order to accurately resolve the field distribution in the vicinity of the defect the elements must be smaller than the finest detail of the defect. This causes computer rounding errors to be significant.

If the mean potential in an element is large the change from node to node can easily be smaller than machine precision. Refinement of the model simply increases the errors. This is a fundamental problem with a finite element method and it can only be avoided by changing the gauge condition applied to the potential, the space can be divided into a set of subspaces, within each an unknown constant is added to the potential in order to make the nodal values of the potentials small. Figure 4 shows the calculated field above a 0.2 micron wide crack, 100 microns deep, both with and without the independent gauge condition (both results were evaluated in double precision).

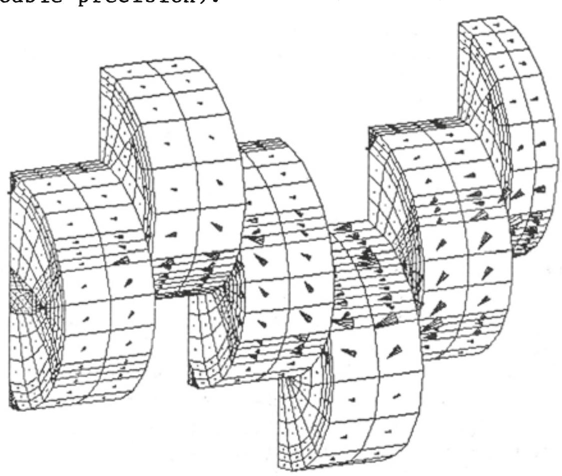

Fig. 3. Crankshaft model

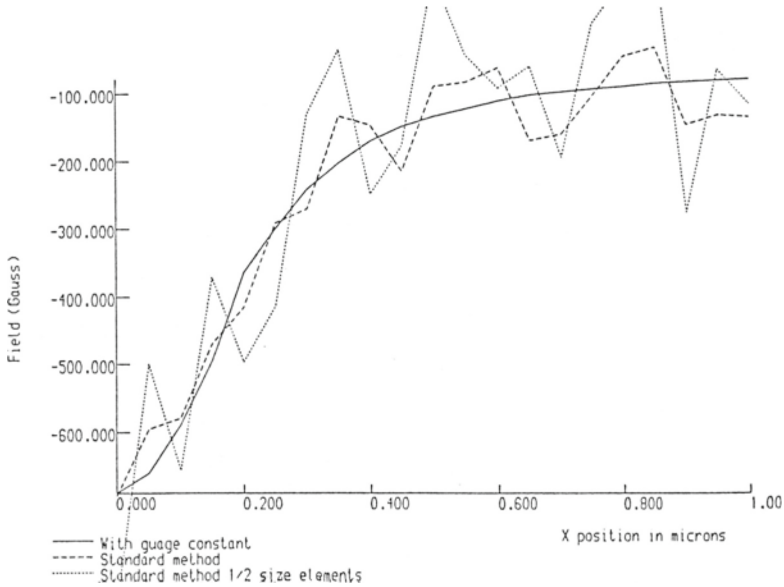

Fig. 4. Stray field above crack (0.2 µm wide, 100 µm deep)

MEASUREMENTS

Crankshaft model

A crankshaft model was fabricated as shown in Figure 3: Diameter of the different hubs are: 50 mm, width: 20 mm, vertical shift: 20 mm. Material: 9 S 20 K (free machining steel). Magnetization was realized using DC as well as AC-50 Hz, applying yoke, coil as well as current. The field strength in air was measured with a Magnetoscop (Institut Dr. Förster), applying Hall-probes under different orientations to determine the axial (H_a), tangential (H_{tg}) and normal (H_n) components.
For the AC- case the surface flux density B was measured in axial (B_a) and tangential (B_{tg}) direction with an ACPD-instrument (DSF1 from Walker sonix, based on a recent development product /14/). The measurements were made at 3 different positions in the middle of each hub. These are 12°°, at the top of the hubs; 3°°, at 90° to this point; 6°°, at the bottom of the hubs.
Mechanical fixtures were used to hold the probes in exact positions. The measurements were independently repeated several times. The reproducibility of the results was within ± 10 %.

Hub

A real suspension part made from cast steel GTW was modeled as shown in Figure 2 representing an AC-50Hz yoke-magnetization (i= 100 A). The value of $|B|$ at the surface was calulated and compared to measurements (i = 400 A) made by yoke-magnetization as well as by yoke- and current-magnetization. Twenty different measuring points were distributed over the surface of the component. The B-measurements were made using the DSF 1 with orientations parallel and perpendicular to the clamping direction between the two yoke-poles. The two measured values were vector-added together to yield $|B|$. The reproducibility was better than ± 10 %, especially too if pure yoke- or yoke- and current-magnetization were compared with each other.

DISCUSSION

Crankshaft model

The comparison between modeling and measurement ref. to H_a is shown in Figures 5, 6 for the coil-magnetizations 500 A-DC and 500 A-AC.
The experimental data are directly drawn. The modelling results are integrals over the spatially varying fields taking into account the two-dimensional extension and the height-position of the Hall-probes. The results comparing H_{tg} and H_n are in the same agreement as shown for H_a.

Besides only a few points the general behaviour shows a good agreement. Quantitatively H_a, H_{tg} and H_n are about the sames for modelling and for experiment in the DC-case. In contrast to this the AC-case gives only agreement if a factor of 2 is fitting experiment to model. This is due to μ_r = 700 used in the calculation and $\mu_r \approx$ 400 at 500 A-AC.

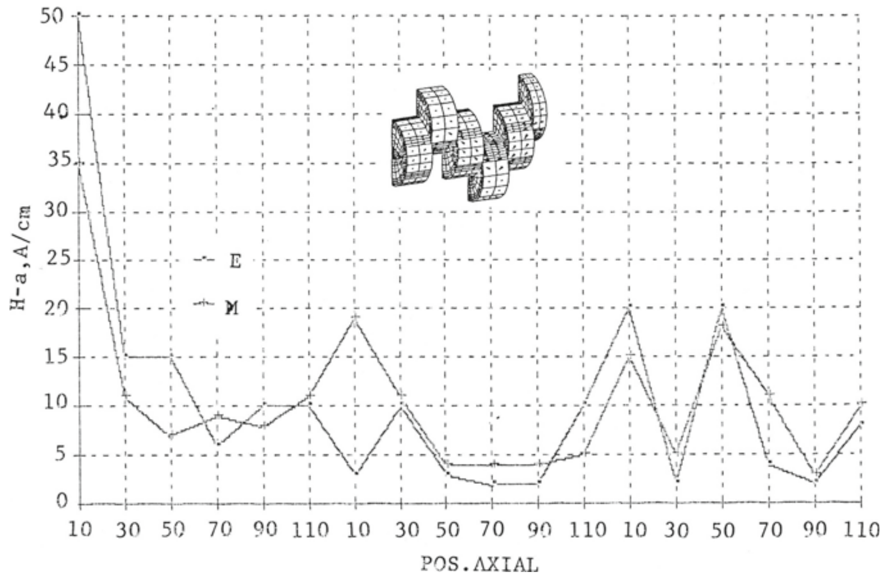

Fig. 5. Comparison model-experiment; crankshaft, coil, 500 A-DC

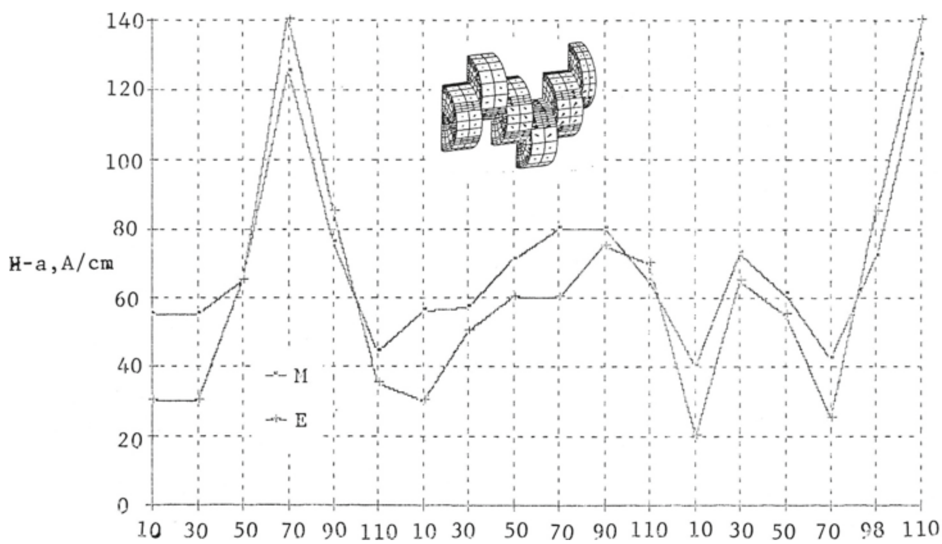

Fig. 6. Comparison model-experiment; crankshaft, coil, 500 A-AC

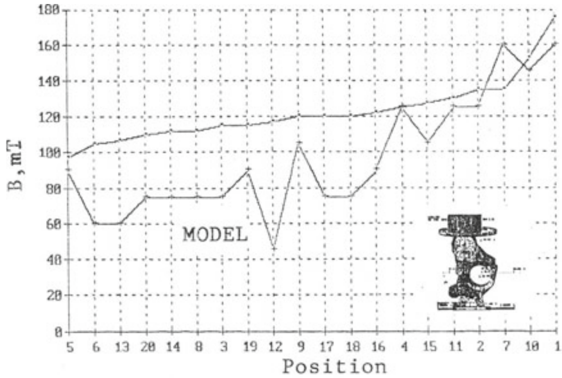

Fig. 7 Comparison model-experiment; hub, yoke, 100 A-AC

Hub

The measured data (divided by 4) show as in the crankshaft-case a general and quantitative agreement with the model (Figure 7) giving still more confidence in the modeling of MPI for complex parts.

CONCLUSION

For the first time MPI of complex shaped components was modelled based on Maxwell's equations and on finite element calulations.
The agreement between modeling and measurement ref. to DC as well as to AC, ref. to coil as well as to yoke magnetization is so good that in the future the design of MPI-systems should be based on modelling results and no longer on trial and error, especially if multi-circuit magnetization is necessary. For specific questions like pulse magnetization, quick break effects, demagnetization, μ(H)-relations etc. there are still problems to be solved by R+D.

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